AMERICAN JOURNAL OF PHYSICAL ANTHROPOLOGY 112:17–27 (2000)

Comparison of Narrow-Band Reflectance Spectroscopy and Tristimulus Colorimetry for Measurements of Skin and Hair Color in Persons of Different Biological Ancestry

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KEY WORDS narrow-band spectrometer; tristimulus colorimeter; skin and hair pigmentation

ABSTRACT We have used two modern computerized handheld reflectometers, the Photovolt ColorWalk colorimeter (a tristimulus colorimeter; Photovolt, UMM Electronics, Indianapolis, IN) and the DermaSpectrometer (a specialized narrow-band reflectometer; Cortex Technology, Hadsund, Denmark), to compare two methods for the objective determination of skin and hair color. These instruments both determine color by measuring the intensity of reflected light of particular wavelengths. The Photovolt ColorWalk instrument does so by shining a white light and sensing the intensity of the reflected light with a linear photodiode array. The ColorWalk results can then be expressed in terms of several standard color systems, most importantly, the Commission International d'Eclairage (CIE) Lab system, in which any color can be described by three values: L*, the lightness; a*, the amount of green or red; and b*, the amount of yellow or blue. Instead of a white light and photodiodes, the DermaSpectrometer uses two light-emitting diodes (LEDs), one green and one red, to illuminate a surface, and then it records the intensity of the reflected light. The results of these readings are expressed in terms of erythema (E) and melanin (M) indices. We measured the unexposed skin of the inner upper arm, the exposed skin of the forehead, and the hair, of 80 persons using these two instruments. Since it is important for the application of these measures in anthropology that we understand their relationship across a number of different pigmentation levels, we sampled persons from several different groups, namely, European Americans (n = 55), African Americans (n = 9), South Asians (n = 7), and East Asians (n = 9). In these subjects, there is a very high correlation between L* and the M index for the inner arm ($R^2 = 0.928$, $P < 0.001$), the forehead ($R^2 = 0.822$, $P < 0.001$), and the hair ($R^2 = 0.827$, $P < 0.001$). The relationship between a* and the E index is complex and dependent on the pigmentation level. We conclude that while both types of instruments provide accurate estimates of pigment level in skin and hair, measurements using narrow-band instruments may be less affected by the greater redness of certain body sites due to increased vascularization. Am J Phys Anthropol 112:17–27, 2000.

Over the past 50 years, skin pigmentation levels have been objectively studied using reflectance spectroscopy. The two instruments that have been most widely used in anthropological studies are the E.E.L. instrument (Evans Electroselenium Co., Hal-

Grant sponsor: NSF; Grant number: 9610332.

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Received 16 December 1998; accepted 13 January 2000.

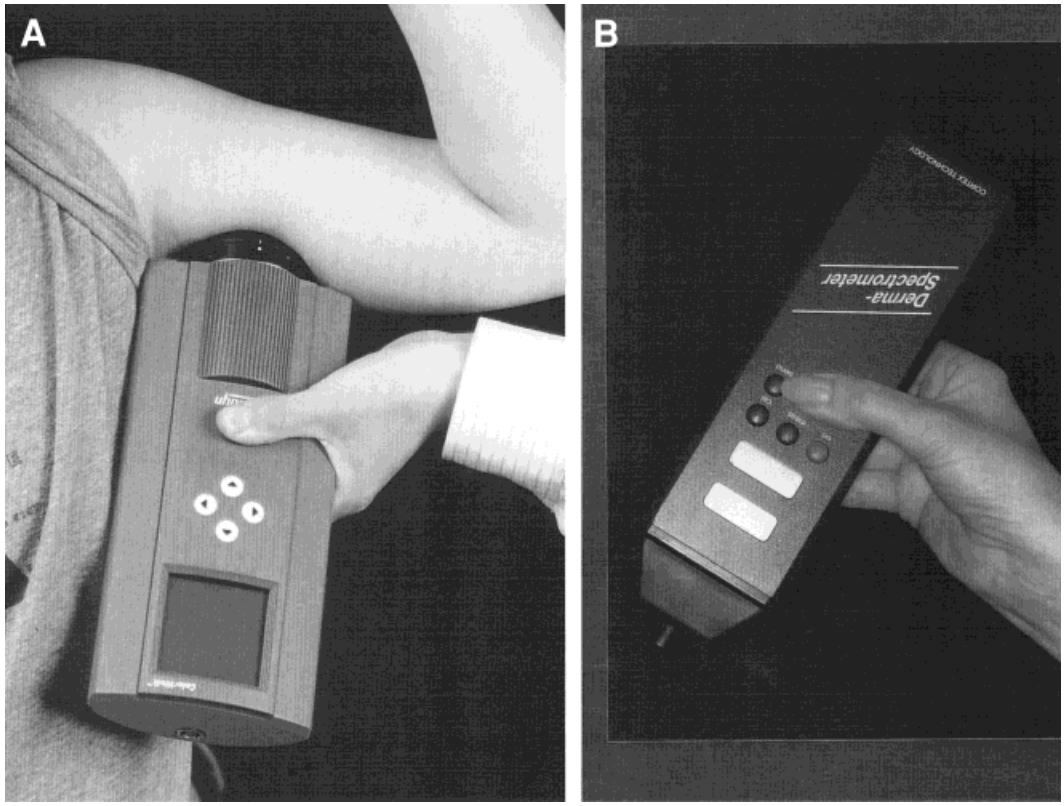

Fig. 1. **A:** Photovolt ColorWalk instrument being used to measure the inner arm of a subject (typically the subject would be seated, as outlined in Subjects and Methods). **B:** DermaSpectometer, in a woman's hand.

stead, Essex, UK) and the Photovolt line of instruments (UMM Electronics, Indianapolis, IN). Both of these instruments use colored filters to measure the percent reflectance of light of various wavelengths. The E.E.L. instruments have a series of nine colored filters, while the original Photovolt systems have six available filters. Although there is much data in the literature on pigmentation levels reported using these E.E.L. and Photovolt filter-based reflectometers (reviewed in Robins, 1991), newer technologies have led to smaller and more accurate devices.

We compared two of these newer instruments for measurements of skin and hair pigmentation, the Photovolt ColorWalk colorimeter (Photovolt, UMM Electronics, Indianapolis, IN) and the DermaSpectrometer (Cortex Technology, Hadsund, Denmark). These instruments apply two different reflectance technologies that have both been widely used in the field of dermatology (Takiwaki et al., 1994, Fullerton et al., 1996). The ColorWalk is a handheld tristimulus colorimeter, which uses photodiode arrays in lieu of colored filters to measure the intensity of particular wavelengths of light (see Fig. 1A). Tristimulus colorimetry was developed as a means of objectively representing color in a manner analogous to the way the eye perceives color (Hunter, 1942). The reflectance level of light through three particular broad wavelength filters (photodiode arrays on newer instruments) is determined. Color parameters are then defined by the levels of and differences among the reflectance levels of these three filters. The most commonly used color parameters are the Commission International d'Eclairage (CIE) L*a*b* system established in 1976. In the CIELab color system,

any color can be represented by three variables: L*, the lightness-darkness axis; a*, the red-green axis; and b*, the blue-yellow axis, which can be plotted in three-dimensional space. Tristimulus colorimeters like the ColorWalk and the commonly used Minolta Chroma Meter 200 and 300 series machines (Minolta Co., Osaka, Japan) are usually able to report color values for a number of other color systems as well.

The DermaSpectrometer is a different type of instrument that was developed specifically for measurements of skin pigments, namely hemoglobin and melanin. The DermaSpectrometer (see Fig. 1B) and related instruments, namely the Erythema/Melanin Meter (DiaStron, DiaStron Ltd., Hampshire, UK) and the Mexameter (Courage Khazaka), are based on the work of Diffey et al. (1984). Hemoglobin and melanin are the principal pigments visible in the skin: hemoglobin in the blood of the capilaries in the dermis, and melanin in the keratinocytes and melanocytes of the epidermis. Hemoglobin and melanin both absorb much light at the lower wavelengths, with hemoglobin showing a large peak in the green wavelengths and then a sharp drop-off, absorbing very little light in the red wavelengths, which is why blood is red. Melanin, both in vivo and in vitro, shows absorbance of light of all wavelengths, essentially a flat line sloping down from the lower wavelengths to the higher wavelengths (Kollias and Baqer, 1985). Based on these differences in the spectral curves of hemoglobin and melanin, Diffey et al. (1984) suggested that the reflectance of narrow-band light in the red spectrum would yield reasonable estimates of the melanin content of a persons skin, following the equation

$$M = \log_{10}(1/\%\ \text{red reflectance}).$$

The degree of skin redness or erythema can be calculated by subtracting the absorbance due to melanin from the absorbance of the green filter and is calculated as

$$E = \log_{10}(1/\%\ \text{green reflectance}) - \log_{10}(1/\%\ \text{red reflectance}).$$

SUBJECTS AND METHODS

Subjects were seated for 5 min with their arms at their sides prior to being measured. While waiting to be measured, they were asked a number of questions, namely, their name, date and place of birth, biological ancestry and ethnicity, and whether they had recently colored their hair. Eighty persons participated in the study: 55 of European ancestry (Europeans or European Americans), 9 of African ancestry (African or African Americans), 7 South Asians (India and Pakistan), and 9 East Asians (China, Taiwan, Philippines, and Korea). All persons were current residents of Pittsburgh, PA or the surrounding areas, and all were measured during the second and third weeks of August 1998. Before use, both instruments were calibrated using the specific white and black calibration standards supplied by the manufacturers. Measurements were first taken with the DermaSpectrometer of the following sites in this order: inner upper right arm, inner upper left arm, forehead, and hair. Three measurements were taken of each site, moving the measurement head a few centimeters between measurements. As has been suggested, care was taken not to apply too much pressure on the measurement head of the DermaSpectrometer, since doing so could occlude blood from the region being measured (Fullerton et al., 1996).

Measurements of the hair were only taken on those persons who said they did not color or bleach their hair. For these measurements, we carefully pressed down the hair throughout the parietal region, making sure that the scalp was not visible, and then applied the measurement head to this area. As with the skin, three measurements were taken in different areas around the parietal, to get a better average of the total level of hair pigmentation. After measuring with the DermaSpectrometer, we measured the same body sites in the same manner with the Photovolt ColorWalk instrument (see Fig. 1A for how a measurement is taken). The ColorWalk allows the user to select among the two commonly used reference illuminants and observation angles in tristimulus colorimetry. As previously suggested by Weatherall and Coombs (1992),

TABLE 1. Summary of the results for melanin content (M and L), and hemoglobin content (E and a*), in the groups included in the present study*[1]

	African Americans (n = 9)			East Asians (n = 9)			European Americans (n = 55)			South Asians (n = 7)		
	Mean	s.d.	CV	Mean	s.d.	CV	Mean	s.d.	CV	Mean	s.d.	CV
M	56.62	14.78	26%	31.79	2.39	8%	30.50	2.82	9%	37.13	4.19	11%
L*	47.50	9.95	21%	67.30	1.62	2%	69.86	3.26	5%	61.90	3.76	6%
E	2.68	5.08	190%	6.92	0.83	12%	6.64	1.20	18%	6.81	0.75	11%
a*	11.17	2.25	20%	12.46	1.21	10%	12.72	1.89	15%	13.25	0.77	6%

[1] s.d., standard deviation; CV, coefficient of variation (s.d./mean)*100.

we used the most recently established standards, namely an observation angle of 10° and the D65 light source.

Both the ColorWalk and the DermaSpectrometer perform internal calculations to convert the raw reflectance readings to the output variables, namely the E and M indices for the DermaSpectrometer, and L*, a*, and b*, in addition to other color systems for the ColorWalk. Linear and nonlinear regression lines were calculated using standard statistical software packages.

RESULTS

Skin

In Table 1, we summarize the results obtained using the ColorWalk and the DermaSpectrometer for measuring the melanin content (M and L*) and hemoglobin content (E and a*) in a sample of 80 individuals from different ethnic groups. Figure 2 shows the relationship between the L* level, the lightness in the CIELab color system, and M, the melanin index, as measured at the inner upper arm, for the 80 persons studied. There is a clear relationship between these two values: as L* decreases, indicating less lightness and less reflectance, the M index increases, indicating higher melanin content in the skin. The linear equation for this line is

$$L^* = 94.15 - 8132M$$

($R^2 = 0.928$, $P < 0.001$). However, it is apparent from the figure that the relationship between L* and M is not strictly linear, especially at high melanin concentrations, and a slightly better fit is obtained using an exponential equation ($R^2 = 0.962$, Table 2). Population differences in pigmentation level are evident in Figure 2. The subjects of European ancestry have the lightest skin, high L*, and low M. Persons of East Asian ancestry have pigment levels which cluster at the lower end of the European distribution. Persons of South Asian ancestry (Indian and Pakistani) are the next darkest group and overlap with some of the African-American subjects, who have the darkest skin as well as the widest variance in pigmentation level.

Figure 3 shows the relationship between L* and M for measurements of the forehead of the 80 subjects studied. As with the measurements of the inner arm, there is a clear correlation between L* and the M index ($R^2 = 0.870$, exponential regression, Table 2). It is also clear that the relationship between L* and M for the forehead is not as strong as for measurements of the inner upper arm.

Both a* and the E index have been used by dermatologists as indicators of the degree of skin redness or erythema (Diffey et al., 1984; Seitz and Whitmore, 1988; Serup and Agner, 1990; Westerhof et al., 1990; Takiwaki et al., 1994). Our data (not shown) indicate that the relationship between a* and E is complex, and dependent on the level of pigmentation. There is a clear positive correlation between a* and E in persons with low melanin content ($M < 40$). However, heavily pigmented persons ($M > 40$) show a much lower correlation and a much less steep relationship between a* and E than lightly pigmented persons.

Given this complex relationship between a* and E, it is important to understand both how E varies with respect to M, and how a* varies with respect to L*. Figures 4 and 5 show the results of these comparisons for measurements of the inner upper arm.

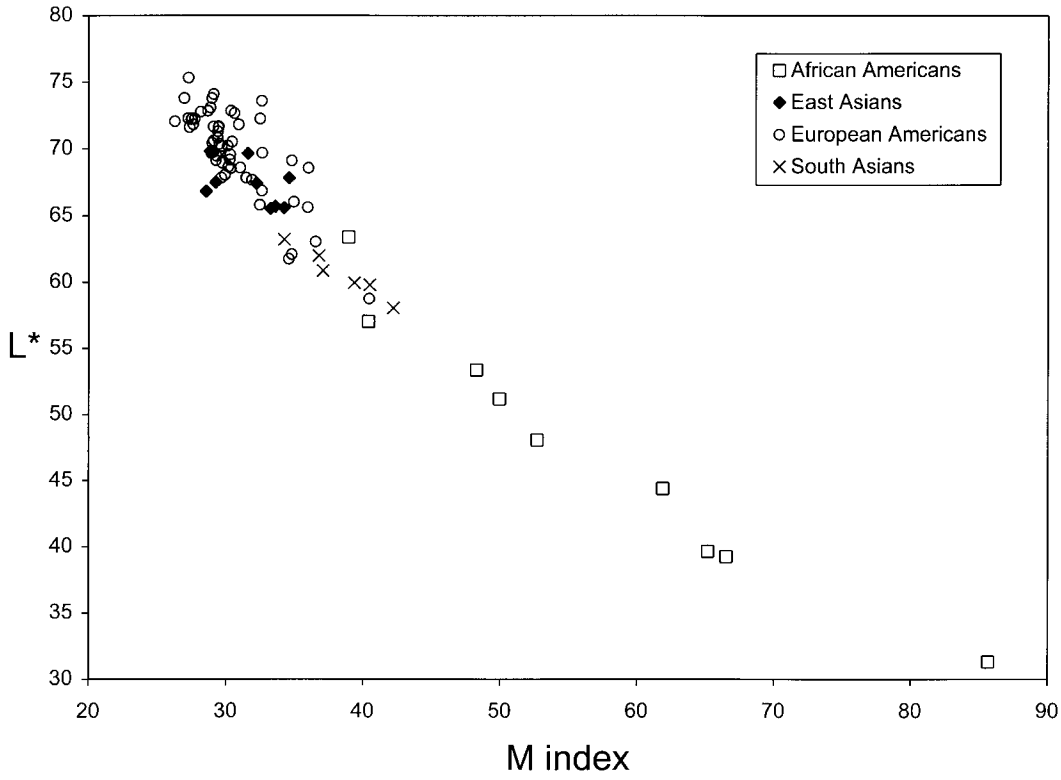

Fig. 2. Relationship between L* and the M index for the inner arm average of all persons measured. L* was measured using the ColorWalk, and the M index using the Dermaspectrometer, as described in Subjects and Methods. Also indicated is the biological ancestry of the persons measured: Europeans and European Americans (open circle), East Asians (solid diamond), South Asians (×), and Africans and African Americans (open square).

TABLE 2. Relationship between the parameters used for estimating melanin content (M and L), as measured in the inner arm, forehead and hair*

	Best fit	R^2
Inner arm		
L* vs. M	$L^* = 110.1e^{-0.0151M}$	0.9617
M vs. L*	$M = 300.53 - 63.646Ln(L^*)$	0.9617
Forehead		
L* vs. M	$L^* = 94.032e^{-0.0127M}$	0.8705
M vs. L*	$M = 317.06 - 68.647Ln(L^*)$	0.8705
Hair		
L* vs. M	$L^* = 167.45 - 30.494Ln(L^*)$	0.8852
M vs. L*	$M = 222.8e^{-0.029L^*}$	0.8852

Again, the relationship between these parameters differs, depending on the level of pigmentation, and there are important differences between the E vs. M plot (Fig. 4) and the plot of a* and L* (Fig. 5). There is no significant correlation between E and M in the groups showing M values lower than 40 (low pigmentation levels, $R^2 = 0.0515$, n.s.), but in persons with M values higher than 40 (high pigmentation levels), a significant negative correlation is observed ($R^2 = 0.976$, $P < 0.001$). On the contrary, the plot of L* vs. a* shows a clear negative correlation in the range corresponding to L* values higher than 60 (low pigmentation levels, $R^2 = 0.565$, $P < 0.001$), and this correlation is not observed in the region of L* values lower than 60 (high pigmentation levels, $R^2 = 0.0000$, n.s.).

Figure 6 shows a histogram of the population distribution of the L* inner upper arm measures for persons of European ancestry. We constructed this histogram using a bin width of two L* units, as suggested by Weatherall and Coombs (1992). The minimum and maximum L* values were 58.7 and 75.3, respectively, and the mode was observed in the range of 71–73 (average L*, 69.9). The L* distribution is highly skewed

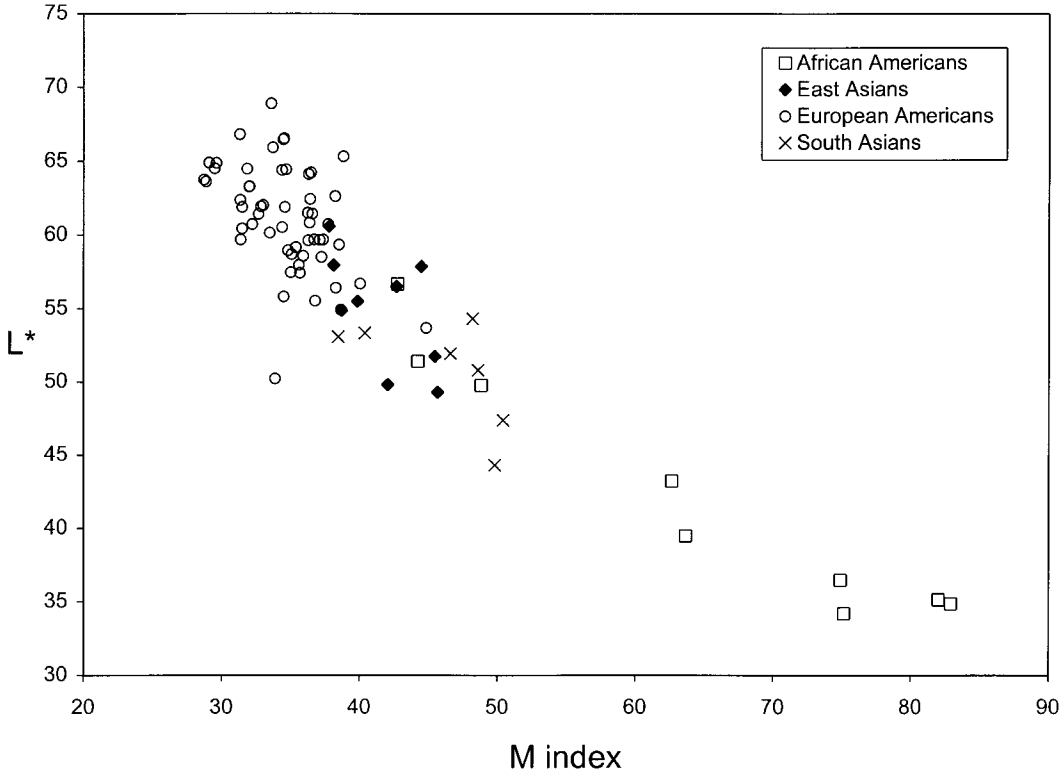

Fig. 3. Relationship between L* and the M index for the forehead average of all persons measured. L* was measured using the ColorWalk and the M index using the Dermaspectrometer as described in Subjects and Methods. Also indicated is the biological ancestry of the persons measured: Europeans and European Americans (open circle), East Asians (solid diamond), South Asians (×), and Africans and African Americans (open square).

and very similar to another report from the literature on the CIE color system in Europeans (Weatherall and Coombs, 1992). The M index showed a very similar distribution, but it was skewed to the right instead of the left (data not shown). Both of these distributions are similar in shape to the log-normal distribution.

Hair

In addition to studies of the skin, reflectometers have been used to objectively quantify the color and degree of pigmentation of the hair (Sunderland, 1956; Little and Wolf, 1981). Figure 7 shows our results for the measurement of the hair of the 64 persons in this survey who did not color or bleach their hair. Figure 7 shows the relationship between L* and the M index for these persons. There is a clear correlation between the two measures L* and M (logarithmic regression, $R^2 = 0.885$, $P < 0.001$). Notable is the limited variability in the hair pigment level of non-European persons. Europeans demonstrate hair reflectance levels that span the range of variation observed.

DISCUSSION

In the present study, we used two handheld reflectometers to compare two methods for the determination of skin and hair color: a narrow-band spectrometer (DermaSpectrometer) and a tristimulus colorimeter (ColorWalk). We sampled persons of different biological ancestry in an effort to span the range of variability in human pigmentation levels. Previous studies were performed by dermatologists in efforts to explore the relationships between the two types of instruments that we consider in this study (e.g., Takiwaki et al., 1994; Fullerton et al., 1996). One important consider-

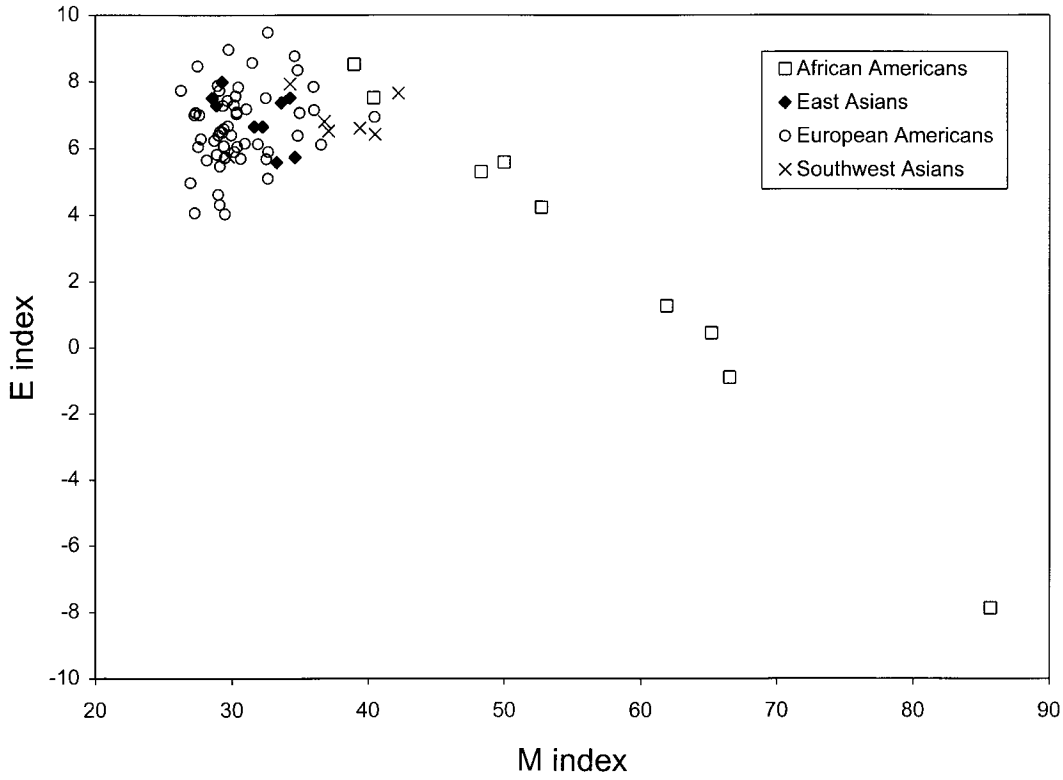

Fig. 4. Relationship between M index and E index for inner upper arm average. Biological ancestry of the persons measured: Europeans and European Americans (open circle), East Asians (solid diamond), Southwest Asians (×), and Africans and African Americans (open square)

ation regarding these studies is that the focus in the dermatological literature has been most often on the measurement of erythema, the reddening of the skin in response to irritation from ultraviolet light or other causes; researchers have not considered the whole range of human pigmentation levels. In contrast, in the anthropological literature, the main focus has been an objective determination of the melanin content of the skin (e.g., Korey, 1980; Relethford et al., 1983; Robins, 1991).

Melanin and hemoglobin are the two dominant chromophores of the skin. The melanin index, M (measured by means of a narrow-band spectrometer), and the L* value of the CIELab space (measured by means of a tristimulus colorimeter) have been used by dermatologists as indicators of the melanin content of the skin. A previous study of 10 individuals of Caucasian ancestry (Takiwaki et al., 1994) reported a moderate but significant negative correlation between M and L* ($R^2 = 0.314$, $P < 0.001$). In our larger sample of persons of European ancestry (n = 55), we observed a higher correlation (upper inner arm, $R^2 = 0.624$, $P < 0.001$), and this correlation is even higher when we include individuals representative of all ethnic groups ($R^2 = 0.928$, $P < 0.001$). Both L* and M seem to be highly correlated with the melanin content of the skin, but the melanin index (M), which has been specifically designed by taking into account the absorbance spectrum of melanin and hemoglobin, may likely be a better indicator of the melanin content than L*. The value of L* is highly dependent on the reflected green light, where in fact hemoglobin has its peak absorption, so that the L* value is not just a function of the melanin concentration. This is clearly indicated by the significant correlation observed between L* and a* in low-pigmented persons (Fig. 5). The more

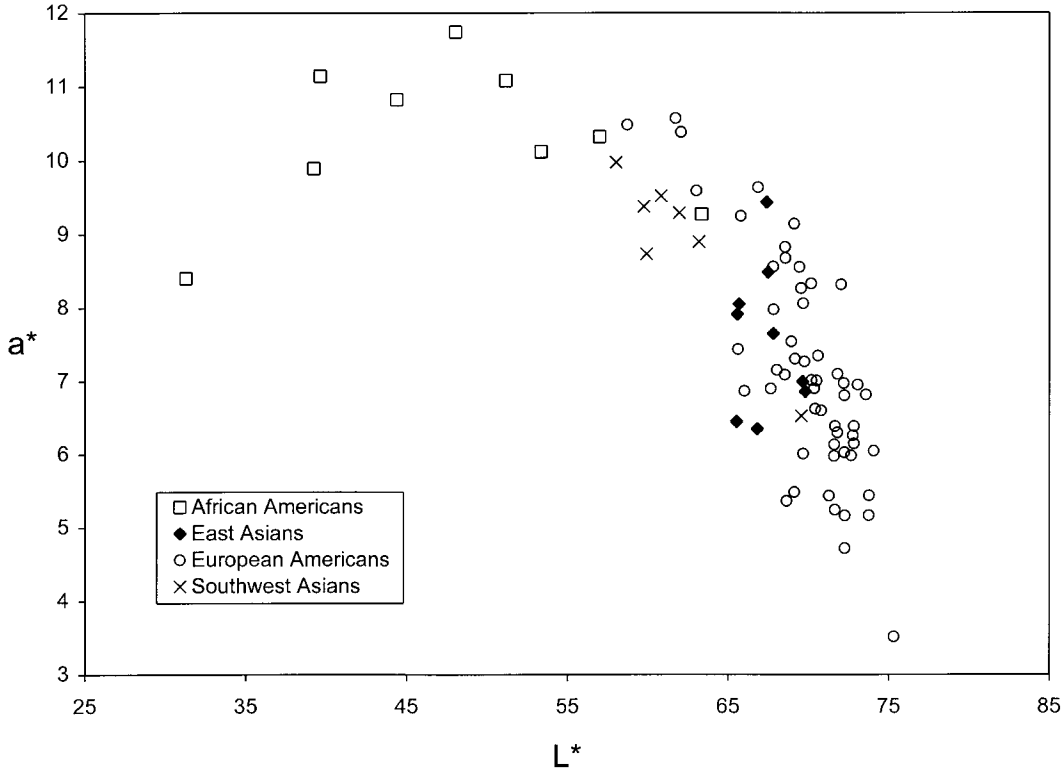

Fig. 5. Relationship between L* and a* for inner upper arm average. Biological ancestry of the persons measured: Europeans and European Americans (open circle), East Asians (solid diamond), Southwest Asians (×), and Africans and African Americans (open square).

red the skin is, the lower the L* is for these persons. This same trend was observed in previous studies (Takiwaki et al., 1994, Fullerton et al., 1996, Takiwaki, 1998), and may be responsible for the decreased correlation of L* and M in some comparisons (e.g., forehead, where there is increased vascularization and sometimes quite dramatic intraindividual variability).

Both a* and the E index have been used by dermatologists as indicators of the degree of skin redness or erythema. A high positive correlation has been observed between a* and E in a small sample of 10 Caucasian male volunteers, in whom measures were taken at 23 different anatomical sites ($R^2 = 0.846$, $P < 0.001$). We observed in our sample of 55 persons of European ancestry a lower, but still significant correlation ($R^2 = 0.379$, $P < 0.001$). However, this correlation is not significant in highly pigmented persons ($M > 40$), indicating the complex relationship between a* and E, and the substantial differences in what both parameters are measuring. This is not surprising, if we take into account the different methodologies upon which the DermaSpectrometer and the ColorWalk are based.

The comparisons of M vs. E and L* vs. a* further stress these differences. M and E are not correlated in low-pigmented groups (Fig. 4). Thus, E is a good indicator of hemoglobin content in those groups, and behaves independently of M. However, in groups characterized by high melanin content, there is a significant negative correlation between E and M ($R^2 = 0.990$, $P < 0.001$), indicating that E is no longer a linear function of hemoglobin content. This is intrinsically due to the methodological principle upon which the calculation of the melanin and erythema indices is based. The melanin index is calculated based on the amount of red light reflected, given that hemoglobin

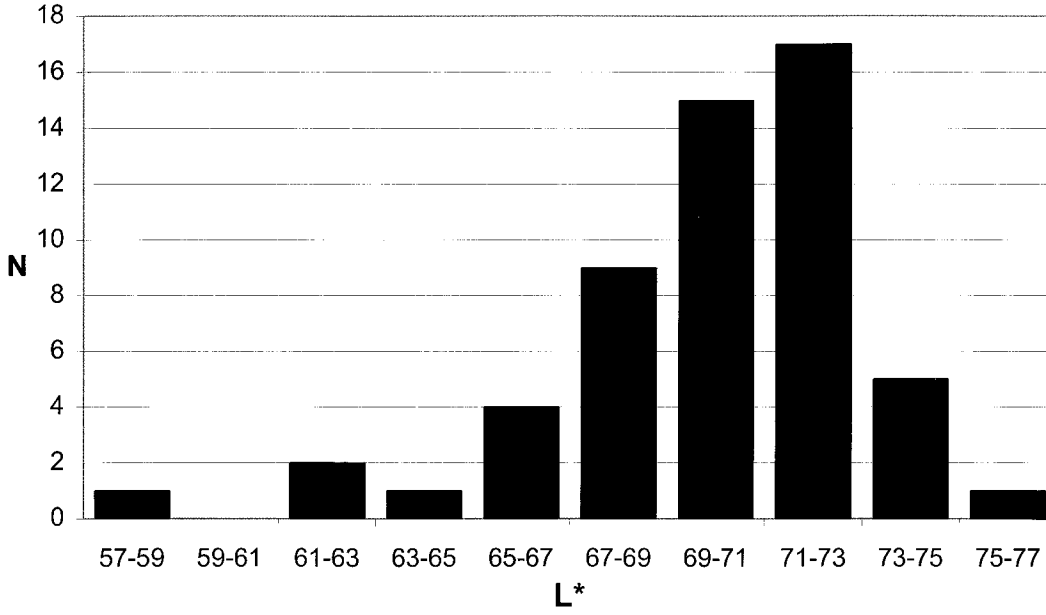

Fig. 6. Population distribution of inner upper arm L* levels for Europeans.

does not absorb in this spectrum, and consequently does not interfere in the calculation of the melanin content. On the contrary, both melanin and hemoglobin absorb light in the green part of the spectrum, and when high concentrations of melanin are present, its effect on the amount of green light reflected is substantial, and the E value is no longer linearly related to the hemoglobin content (Takiwaki et al., 1994). When we consider the relationship between L* and a*, exactly the opposite trend is observed. These values are highly correlated when the amount of melanin is low, but there is no significant correlation when the melanin level is high (Fig. 5).

CONCLUSIONS

With recent technical advances in the field of colorimetry and photometry, new instruments have become available which offer substantial advantages over previously used instruments, in terms of precision, portability, and ease of use. In this paper, we used two new handheld reflectometers, the Photovolt ColorWalk (a tristimulus colorimeter) and the DermaSpectrometer (a specialized narrow-band reflectometer), to compare two methods for the objective determination of skin and hair color. Both instruments operate based on two different principles. Our results indicate that both types of instruments provide good and correlated estimates of pigment level in skin and hair. However, we find that measurements using narrow-band instruments (DermaSpectrometer, in this study) appear to be less affected by the increased redness of certain body sites due to increased vascularization. It is also evident that E and a*, the parameters normally employed for evaluating the degree of erythema, show a complex relationship, which is dependent on the melanin content of the skin.

It is necessary to point out that there are a number of portable and handheld true spectrophotometers currently available (e.g., the spectrophotometer CM-500 and CM-2000 series by Minolta, Japan, and the Microflash series by Datacolor International, Charlotte, NC). Although somewhat more expensive (2–3 times the cost of the instruments we used in this study; $4,995 for the ColorWalk, and $4,500 for the DermaSpectrometer), these spectrophotometers are more versatile in that they measure the reflectance at regular intervals across the spectrum of visible light (400–

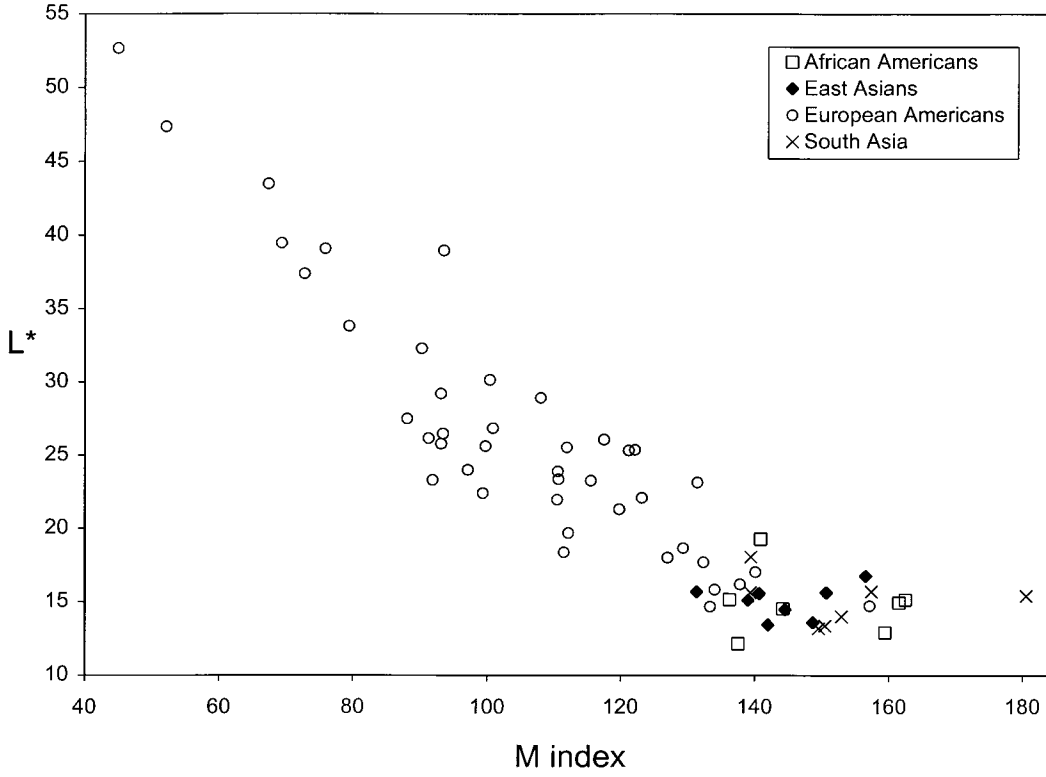

Fig. 7. Relationship between the M index and L* for hair. Biological ancestry of the persons measured: Europeans and European Americans (open circle), East Asians (solid diamond), South Asians (×), and Africans and African Americans (open square).

700 nm). Both have internal software, which computes values for different color systems, including CIELab. Since these instruments can display and record reflectance levels at narrow intervals across the visual spectrum, one could also calculate the E and M indices using these instruments. Additionally, having reflectance information across the whole visible spectrum would make it possible to better distinguish the effect of diverse skin chromophores (melanin, oxy- and deoxy-hemoglobin, bilirubin), and even different forms of melanin (high and low molecular weight melanin, Kollias and Baqer, 1987, 1988; and potentially, eumelanin and pheomelanin).

In summary, both the DermaSpectrometer and the ColorWalk provide accurate and objective measurements of skin and hair color, which are highly correlated (Fullerton et al., 1996; Takiwaki, 1998). In anthropological and genetic studies where the primary aim is the determination of skin pigmentation due to melanin, the DermaSpectrometer would likely be the preferred instrument, as the M index obtained with this apparatus is less confounded by levels of hemoglobin and thus better reflects the amount of melanin present in the skin. This is especially true if comparisons of different body sites will be made (see also Lock-Andersen and Wulf, 1998). In lightly pigmented persons, differences in degree of vascularization of different body sites make the use of L* troublesome for these types of comparisons.

ACKNOWLEDGMENTS

We thank all of the participants in this study for their willingness and cooperation. This study was funded in part by NSF grant 9610332 to M.S. We also thank Dr. Gary Grove of cyberDERM, Inc. (Media, PA) for the loan of the DermaSpectrometer, as well

as the Editor and four reviewers for their constructive comments on this manuscript.

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